NSF-ITP-95-140, UPR-0683T
October 31, 1995

Precision Experiments, Grand Unification, and Compositeness[1]

Paul Langacker

University of Pennsylvania, Department of Physics
Philadelphia, Pennsylvania, USA 19104-6396

and

Institute for Theoretical Physics,
University of California, Santa Barbara, CA 93106-4030

Abstract

Precision electroweak data allow one to test the standard model, constrain its parameters, and search for the effects of some kinds of new physics. The results of the most recent data from LEP, SLC, and elsewhere are described, as are their predictions for m_t, M_H, and α_s. The implications for the two major classes of extensions of the standard model, supersymmetry/unification and compositeness, are described.

1 Recent Data

The four LEP experiments ALEPH, DELPHI, L3, and OPAL have recently presented combined results at the Brussels Europhysics Conference and at the Lepton-Photon conference in Beijing. These include preliminary results from the 1994 run, and altogether include nearly 14 million events. The averages include a proper treatment of common systematic uncertainties [5]. Similarly, the SLD experiment at the SLC [6] has presented new results on the left-right asymmetry A_{LR}, including the data from the very successful 1994-1995 run, as well as the first direct determination of final state couplings of the b and c. The major Z-pole results are shown in Table 1. The first row gives the value of the Z mass, which is now known to remarkable precision. Also shown are the lineshape variables Γ_Z, R, and $\sigma_{\rm had}$; the heavy quark production rates; various forward-backward asymmetries, A_{FB}; quantities derived from the τ polarization P_τ and its angular distribution; final state b and c couplings determined by SLD from mixed polarization forward-backward asymmetries; and the effective weak angle $\bar{s}^2_\ell$ obtained from the jet charge asymmetry. N_ν is the number of effective active neutrino flavors with masses light enough to be produced in Z decays. It is obtained by subtracting the widths for decays into hadrons and charged leptons from the total width Γ_Z from the lineshape. The asymmetries are expressed in terms of the quantity

$$A^o_f = \frac{2\bar{g}_{Vf}\,\bar{g}_{Af}}{\bar{g}^2_{Vf} + \bar{g}^2_{Af}}, \tag{1}$$

[1] Invited talk presented at *SUSY-95*, Palaiseau, France, May 1995. The results presented here are from a collaboration with Jens Erler. For more details, see [1].

Quantity	Value	Standard Model
M_Z (GeV)	91.1884 ± 0.0022	input
Γ_Z (GeV)	2.4963 ± 0.0032	$2.497 \pm 0.001 \pm 0.002 \pm [0.002]$
$R = \Gamma(\mathrm{had})/\Gamma(\ell\bar{\ell})$	20.788 ± 0.032	$20.77 \pm 0.004 \pm 0.002 \pm [0.02]$
$\sigma_{\mathrm{had}} = \frac{12\pi}{M_Z^2} \frac{\Gamma(e\bar{e})\Gamma(\mathrm{had})}{\Gamma_Z^2}$(nb)	41.488 ± 0.078	$41.45 \pm 0.002 \pm 0.004 \pm [0.02]$
$R_b = \Gamma(b\bar{b})/\Gamma(\mathrm{had})$	0.2219 ± 0.0017	$0.2156 \pm 0 \pm 0.0003$
$R_c = \Gamma(c\bar{c})/\Gamma(\mathrm{had})$	0.1540 ± 0.0074	$0.172 \pm 0 \pm 0$
$A_{FB}^{0\ell} = \frac{3}{4}\left(A_\ell^0\right)^2$	0.0172 ± 0.0012	$0.0155 \pm 0.0004 \pm 0.0004$
$A_\tau^0\,(P_\tau)$	0.1418 ± 0.0075	$0.144 \pm 0.002 \pm 0.002$
$A_e^0\,(P_\tau)$	0.1390 ± 0.0089	$0.144 \pm 0.002 \pm 0.002$
$A_{FB}^{0b} = \frac{3}{4} A_e^0 A_b^0$	0.0997 ± 0.0031	$0.101 \pm 0.001 \pm 0.001$
$A_{FB}^{0c} = \frac{3}{4} A_e^0 A_c^0$	0.0729 ± 0.0058	$0.072 \pm 0.001 \pm 0.001$
$\bar{s}_\ell^2\left(A_{FB}^Q\right)$	0.2325 ± 0.0013	$0.2319 \pm 0.0002 \pm 0.0002$
$A_e^0\,(A_{LR}^0)$ (SLD)	0.1551 ± 0.0040	$0.144 \pm 0.002 \pm 0.002$
A_b^0 (SLD)	0.841 ± 0.053	$0.934 \pm 0 \pm 0$
A_c^0 (SLD)	0.606 ± 0.090	$0.667 \pm 0.001 \pm 0.001$
N_ν	2.991 ± 0.016	3

Table 1: Z-pole observables from LEP and SLD compared to their standard model expectations. The standard model prediction is based on M_Z and uses the global best fit values for m_t and α_s, with M_H in the range $60 - 1000$ GeV.

where $\bar{g}_{V,Af}$ are the vector and axial vector couplings to fermion f.

From the Z mass one can predict the other observables, including electroweak loop effects. The predictions also depend on the top quark and Higgs mass, and α_s is needed for the QCD corrections to the hadronic widths. The predictions are shown in the third column of Table 1, using the value $m_t = 180 \pm 7$ GeV obtained for $M_H = 300$ GeV in a global best fit to all data (including the direct determination $m_t = 180 \pm 12$ GeV by CDF [7] and DO [8]). The first uncertainty is from M_Z and Δr (related to the running[2] of α up to M_Z), while the second is from m_t and M_H, allowing the Higgs mass to vary in the range $60 - 1000$ GeV. The last uncertainty is the QCD uncertainty from the value of α_s. Here the value and uncertainty are given by $\alpha_s = 0.123 \pm 0.004$, obtained from the global fit to the lineshape.

The data is generally in excellent agreement with the standard model predictions. However,

$$R_b = \frac{\Gamma(b\bar{b})}{\Gamma(\mathrm{had})} = 0.2219 \pm 0.0017 \tag{2}$$

is 3.7σ higher than the standard model expectation, while $R_c = \Gamma(c\bar{c})/\Gamma(\mathrm{had})$ is 2.4σ below. These are correlated: if R_c is fixed at the standard model value of 0.172, then [5] $R_b = 0.2205 \pm 0.0016$, which is still 3.0σ too high. Within the standard model framework, these must be considered statistical fluctuations or systematic errors. However, because of special vertex corrections, the $b\bar{b}$ width actually decreases with m_t, as opposed to the other widths which all increase. This can be seen in Figure 1. Thus, R_b favors low values for m_t. By itself R_b is insensitive to the Higgs mass M_H, but when combined with other observables, for which the t quark and Higgs mass M_H are strongly correlated, R_b favors low values for M_H. Another possibility, if the effect is more than a statistical fluctuation, is that it may be due to some sort of new physics. Many types of new physics will couple preferentially to the third generation,

[2]There have been several recent reevaluations [9]-[12] of the hadronic contribution to the running of α. Following a correction to [12] these are in reasonable agreement. We use $\alpha(M_Z)^{-1} = 128.09 \pm 0.09$ from [9].

Figure 1: Standard model prediction for $R_b \equiv \Gamma(b\bar{b})/\Gamma(\text{had})$ as a function of m_t, compared with the LEP experimental value. Also shown is the range 180 ± 12 GeV determined by the direct CDF and D0 observations.

so this is a serious possibility. As will be seen below, the possibility of new physics in the $Zb\bar{b}$ vertex is strongly correlated with the value of α_s extracted from the Z lineshape.

Another discrepancy is the value of the left-right asymmetry

$$A^0_{LR} = A^0_e = 0.1551 \pm 0.0040 \tag{3}$$

obtained by the SLD collaboration using all data from 1992-1995. This value has moved closer to the standard model expectation of 0.144 ± 0.003 than the previous value of 0.1637 ± 0.0075 from 1992-1993. However, because of the smaller error it is still some 2.3σ higher than the standard model prediction. This result (combined with M_Z) favors a large value of the top quark mass, around 220 GeV, which is not in good agreement with other observables. One possibility is that it is pointing to new physics. Possibilities here would include $S < 0$, where S is a parameter describing certain types of heavy new physics (see Section 3.6). In addition, there are possible tree-level physics such as heavy Z' bosons or mixing with heavy exotic doublet leptons, E'_R, which could significantly affect the asymmetry. However, new physics probably cannot explain all of the discrepancy with the other observables, because some of the LEP observables measure precisely the same combination of couplings as does A_{LR}[3]. In particular, from the LEP measurements of $A^{0\ell}_{FB}$, $A^0_e(P_\tau)$, and $A^0_\tau(P_\tau)$ one can obtain an average $A^0_{\ell\text{LEP}} = 0.147 \pm 0.004$, consistent with the standard model prediction but 1.5σ below A^0_{LR}. If one does not assume lepton family universality, the LEP observables A^{0e}_{FB} and $A^0_e(P_\tau)$ imply $A^0_{e\text{LEP}} = 0.141 \pm 0.007$, 1.7σ below A^0_{LR}.

Finally, the forward-backward asymmetry into τ's, $A^{0\tau}_{FB} = 0.0206 \pm 0.0023$ is 2.2σ above the standard model prediction, and 1.6σ above the average 0.0162 ± 0.0014 of $A^{0\mu}_{FB}$ and A^{0e}_{FB}. This is small enough to be a fluctuation, so we will assume lepton flavor universality.

There are many other precision observables. Some recent ones are shown in Table 2. These include the W mass from CDF, D0, and UA2 [14], the effective weak charge Q_W measured in atomic parity violation in cesium [15], recent results on the effective vector and axial couplings measured in neutrino electron scattering from CHARM II [16], and measurements of $s^2_W \equiv 1 - M^2_W/M^2_Z$ from the CCFR collaboration at Fermilab [17]. This on-shell definition of the weak angle is determined from deep inelastic neutrino scattering with small sensitivity to the

[3]The relation makes use only of the assumption that the LEP and SLD observables are dominated by the Z-pole. The one loophole is the possibility of an important contribution from other sources, such as new 4-fermi operators. These are mainly significant slightly away from the pole (at the pole they are out of phase with the Z amplitude and do not interfere). However, a combined analysis of all constraints renders this possibility unlikely [13].

Quantity	Value	Standard Model
M_W (GeV)	80.26 ± 0.16	$80.34 \pm 0.01 \pm 0.04$
$Q_W(C_S)$	$-71.04 \pm 1.58 \pm [0.88]$	$-72.88 \pm 0.05 \pm 0.03$
$g_A^{\nu e}$ (CHARM II)	-0.503 ± 0.017	$-0.507 \pm 0 \pm 0.0004$
$g_V^{\nu e}$ (CHARM II)	-0.035 ± 0.017	$-0.037 \pm 0.0005 \pm 0.0003$
$s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$	0.2218 ± 0.0059 [CCFR] 0.2260 ± 0.0048 [All]	$0.2237 \pm 0.0002 \pm 0.0008$
M_H (GeV)	≥ 60 LEP	$< \begin{cases} 0(600), \text{ theory} \\ 0(800), \text{ indirect} \end{cases}$
m_t	180 ± 12 CDF/D0	$179 \pm 8^{+17}_{-20}$ [indirect]

Table 2: Recent observables from the W mass and other non-Z-pole observations compared with the standard model expectations. Direct limits and values on M_H and m_t are also shown.

Figure 2: Values of $\sin^2 \hat{\theta}_W(M_Z)$ as a function of m_t from various observables.

top quark mass. The result combined with earlier experiments [18] is also shown. All of these quantities are in excellent agreement with the standard model predictions.

In the global fits to be described, all of the earlier low energy observables not listed in the table are fully incorporated. The electroweak corrections are now quite important. The results presented include full 1-loop corrections, as well as dominant 2-loop effects, QCD corrections, and mixed QCD-electroweak corrections. For the renormalized weak angle, I use the modified minimal subtraction ($\overline{MS}$) definition [19] $\sin^2 \hat{\theta}_W(M_Z) \equiv \hat{s}_Z^2$. This basically means that one removes the $\frac{1}{n-4}$ poles and some associated constants from the gauge couplings. Other definitions are reviewed in [1, 3].The values of $\hat{s}_Z^2$ obtained from various observables as a function of m_t are shown in figure 2.

2 Results: m_t, M_H, α_s, $\sin^2 \theta_W$

There are now sufficiently many observables that one can determine $\hat{s}_Z^2$, m_t, and $\alpha_s(M_Z)$ from the Z-pole and other indirect precision data simultaneously. For example, $\hat{s}_Z^2$ can be determined from the asymmetries, m_t from the W and Z masses, and $\alpha_s(M_Z)$ from the hadronic Z-widths. In practice all of these quantities are determined from a simultaneous fit. The results of fits to various sets of data are shown in Table 3. The first row of the table shows the global fit to all data, including the direct production constraint $m_t = 180 \pm 12$ GeV from CDF and D0. The second row uses the indirect data only. The predicted value of $m_t = 179 \pm 8^{+17}_{-20}$ GeV is in remarkable agreement with the CDF/D0 value. The other fits show the sensitivity to the various data sets.

Set	$\hat{s}^2_Z$	$\alpha_s(M_Z)$	m_t (GeV)	$\Delta\chi^2_H$
Indirect + CDF + D0	0.2315(2)(3)	0.123(4)(2)	$180 \pm 7^{+12}_{-13}$	7.9
Indirect	0.2315(2)(2)	0.123(4)(2)	$179 \pm 8^{+17}_{-20}$	8.5
LEP	0.2318(3)(2)	0.124(4)(2)	$171 \pm 10^{+18}_{-20}$	5.7
Z-pole (LEP + SLD)	0.2314(3)(1)	0.123(4)(2)	$181^{+8}_{-9}{}^{+18}_{-20}$	8.3
SLD + M_Z	0.2302(5)(0)	—	$220^{+14}_{-15}{}^{+19}_{-24}$	

Table 3: Results for the electroweak parameters in the standard model from various sets of data. The central values assume $M_H = 300$ GeV, while the second errors are for $M_H \to 1000(+)$ and $60(-)$. The last column is the increase in the overall χ^2 of the fit as M_H increases from 60 to 1000.

The LEP data allows a determination of the strong coupling constant α_s at the Z-pole with a small experimental error,

$$\alpha_s(M_Z) = 0.123 \pm 0.004 \pm 0.002 \quad \text{(lineshape)}, \tag{4}$$

where the second uncertainty is from M_H. α_s is almost uncorrelated with the other parameters. It is determined mainly from the ratio $R \equiv \Gamma(\text{had})/\Gamma(\ell\bar{\ell})$, which is insensitive to m_t (except in the $b\bar{b}$ vertex), and also from Γ_Z. This determination is very clean theoretically, at least within the standard model. It is the Z-pole version of the long held view that the ratio of hadronic to leptonic rates in e^+e^- would be a "gold plated" extraction of α_s and test of QCD. Using a recent estimate [20] of the $(\alpha_s/\pi)^4$ corrections to C_F, *i.e.* $-90(\alpha_s/\pi)^4$, one can estimate that higher-order terms lead to an additional uncertainty $\sim \pm 0.001$ in the $\alpha_s(M_Z)$ value in (4). It should be cautioned, however, that the lineshape value is rather sensitive to the presence of some types of new physics which affect the Z-hadron width, as is discussed below.

The lineshape value of α_s is in excellent agreement with the independent value $\alpha_s(M_Z) = 0.123 \pm 0.006$ extracted from jet event shapes at LEP using resummed QCD [24]. It is also in agreement with the prediction

$$\alpha_s(M_Z) \sim 0.130 \pm 0.010, \qquad \text{SUSY} - \text{GUT} \tag{5}$$

of supersymmetric grand unification[4] [21, 22]. As can be seen in Table 4, however, it is somewhat larger than some of the low energy determinations of α_s (which are then extrapolated theoretically to the Z-pole), in particular those from deep inelastic scattering and the lattice calculations of the charmonium and bottomonium spectra. This slight discrepancy has led some authors to suggest that there might be a light gluino which would modify the running of α_s, or that there is a problem in the high energy determinations [23]. I think, however, that it is premature to draw such strong conclusions, especially since most of the determinations are dominated by theoretical uncertainties.

There is, however, one significant uncertainty in the lineshape value: if the high experimental value of R_b is due to a new physics contribution to the $Z \to b\bar{b}$ vertex, and not just a fluctuation, then the formulae for R and Γ_Z are affected, and the value of $\alpha_s(M_Z)$ extracted from the lineshape is reduced [3]. Allowing for that possibility, one finds the lower value $\alpha_s(M_Z) = 0.101 \pm 0.008$, in better agreement with some of the low energy determinations.

One could also consider the possibility that the low value of R_c is due to new physics. However, allowing for that possibility, one obtains $\alpha_s(M_Z) = 0.19 \pm 0.03$ or 0.16 ± 0.04, where the former (latter) value does not (does) allow for new physics in R_b as well. The first value in

[4]In this case one should actually use the value $\alpha_s(M_Z) = 0.121(4)(1)$ appropriate to the lower Higgs range expected in the supersymmetric extension of the standard model.

Source	$\alpha_s(M_Z)$
R_τ	0.122 ± 0.005
Deep inelastic	0.112 ± 0.005
Υ, J/Ψ	0.113 ± 0.006
$c\bar{c}$ spectrum (lattice)	0.110 ± 0.006
$b\bar{b}$ spectrum (lattice)	0.115 ± 0.002
LEP, lineshape	0.123 ± 0.004
LEP, event topologies	0.123 ± 0.006

Table 4: Values of α_s at the Z-pole extracted from various methods.

Figure 3: Allowed regions in m_t vs. M_H at various confidence levels. The direct constraint $M_H > 60$ GeV is also indicated.

particular is in clear disagreement with other determinations, so I will take the view that R_c is a statistical fluctuation.

2.1 The Higgs Mass

The new data significantly constrain the Higgs boson mass. This enters the relation between M_Z and the other observables logarithmically and is strongly correlated with the quadratic m_t dependence in everything but the $Z \to b\bar{b}$ vertex correction. The data strongly favor a Higgs mass near the direct lower limit of ~ 60 GeV. This can be seen in the last column of Table 3, which lists the increase in χ^2 for the overall fits as M_H increases from 60 to 1000 GeV. For example, in the fit to all data (including the direct constraints) the best fit is for $M_H = 60$ GeV, with the limit $M_H < 320(430)$ GeV at 90(95)% CL. The allowed regions in m_t vs. M_H at various confidence levels are shown in Figure 3.

These low values for M_H are consistent with the minimal supersymmetric extension of the standard model, which generally predicts a relatively light standard model-like Higgs scalar. However, a strong caveat is in order: the preference for small M_H is driven almost entirely by R_b and A^0_{LR}, both of which differ significantly from the standard model predictions. If these are due to large statistical fluctuations or to some new physics then the constraint on M_H would essentially disappear.

The weak M_H dependence does not imply that the data is insensitive to the spontaneous symmetry breaking mechanisms. Alternative schemes generally yield large effects on the precision observables, as will be described below.

3 New Physics

3.1 Supersymmetry and Precision Experiments

Let us now consider how the predictions for the precision observables are modified in the presence of supersymmetry. There are basically three implications for the precision results. The first, and most important, is in the Higgs sector. In the standard model the Higgs mass is arbitrary. It is controlled by an arbitrary quartic Higgs coupling, so that M_H could be as small as 60 GeV (the experimental limit) or as heavy as a TeV. The upper bound is not rigorous: larger values of M_H would correspond to such large quartic couplings that perturbation theory would break down. This cannot be excluded, but would lead to a theory that is qualitatively different from the (perturbative) standard model. In particular, there are fairly convincing triviality arguments, related to the running of the quartic coupling, which exclude a Higgs which acts like a distinct elementary particle for M_H above $O(600\text{ GeV})$ [25].

However, in supersymmetric extensions of the standard model the quartic coupling is no longer a free parameter. It is given by the squares of gauge couplings, with the result that all supersymmetric models have at least one Higgs scalar that is relatively light, typically with a mass similar to the Z mass. In the minimal supersymmetric standard model (MSSM) one has $M_H < 150$ GeV[5], which generally acts just like the standard model Higgs[6] except that it is necessarily light.

In the standard model there is a large $m_t - M_H$ correlation, and the global fit yields

$$m_t \sim 180 \pm 7 + 13 \ln \left(\frac{M_H}{300\text{GeV}} \right). \tag{6}$$

We have seen that for $60 < M_H < 1000$ GeV this corresponds to

$$m_t = 180 \pm 7^{+12}_{-13} \text{ (SM)}. \tag{7}$$

However, in the MSSM one has the smaller range $60 < M_H < 150$ GeV, leading to

$$m_t = 169 \pm 7^{+4}_{-3} \text{ (MSSM)}, \tag{8}$$

which is on the lower side of the CDF/D0 range, $(180 \pm 12$ GeV). Because of the lower m_t, one obtains $\hat{s}^2_Z = 0.2313(2)(1)$ and $\alpha_s(M_Z) = 0.121 \pm 0.004^{+0.001}_{-0}$, which differ slightly from the values in Table 3.

There can be additional effects on the radiative corrections due to sparticles and the second Higgs doublet that must be present in the MSSM. However, for most of the allowed parameter space one has $M_{\text{new}} \gg M_Z$, and the effects are negligible by the decoupling theorem. For example, a large $\tilde{t} - \tilde{b}$ splitting would contribute to the ρ_0 (SU_2-breaking) parameter (to be discussed below), leading to a smaller prediction for m_t, but these effects are negligible for $m_{\tilde{q}} \gg M_Z$. Similarly, there would be new contributions to the $Z \to b\bar{b}$ vertex for $m_{\chi^\pm}$, $m_{\tilde{t}}$, or $M_H^\pm \sim M_Z$. The MSSM yields a better fit to the precision data than the standard model [26], but that is mainly due to the anomalous experimental value of R_b.

There are only small windows of allowed parameter space for which the new particles contribute significantly to the radiative corrections. Except for these, the only implications of supersymmetry from the precision observables are: (a) there is a light standard model-like Higgs, which in turn favors a smaller value of m_t. Of course, if a light Higgs were observed it would be consistent with supersymmetry but would not by itself establish it. That would

[5] At tree-level, $M_H < M_Z$.

[6] This is true if the second Higgs doublet is much heavier than M_Z.

require the direct discovery of the superpartners, probably at the LHC. (b) Another important implication of supersymmetry, at least in the minimal model, is the *absence* of other deviations from the standard model predictions. (c) In supersymmetric grand unification one expects the gauge coupling constants to unify when extrapolated from their low energy values [21]. This is consistent with the data in the MSSM but not in the ordinary standard model (unless other new particles or thresholds are added). This is not actually a modification of the precision experiments, but a prediction for the observed gauge couplings. Of course, one could have supersymmetry without grand unification.

3.2 Unification of Gauge Couplings

It is now well known that the (properly normalized) observed gauge couplings do not unify when extrapolated to a large scale using the standard model predictions for the running, but they do within experimental uncertainties if they run according to the MSSM [21]. Since the electroweak couplings $\alpha(M_Z)$ and $\hat{s}^2_Z$ are known precisely, it is useful to use them as inputs to predict the more uncertain α_s [22]. Using present data, one predicts $\alpha_s(M_Z) = 0.130 \pm 0.001 \pm 0.010$, where the first uncertainty is from the input couplings and the second is an estimate of the theoretical uncertainties from the low energy (supersymmetry) and superheavy (grand unification) thresholds, and from possible nonrenormalizble operators (NRO). As discussed in Section 2, this is in good agreement with the experimental values determined from the Z lineshape and from the LEP jet event analysis, but is high compared with some low energy detrminations of $\alpha_s(M_Z)$. In contrast, the non-supersymmetric standard model prediction is $0.073 \pm 0.001 \pm 0.001$, well below the experimental values.

Thus, the observed couplings are consistent to first approximation with simple supersymmetric grand unification and the associated concept of a grand desert between the TeV and GUT scales. However:

- Threshold corrections associated with the supersymmetric particles are > -0.003 and are usually positive assuming universal soft supersymmetry breaking terms [27], and supersymmetric contributions to the electroweak radiative corrections generally lead to larger $\alpha_s(M_Z)$ [27]. Thus, low-scale threshold effects are not likely by themselves[7] to lower the predicted $\alpha_s(M_Z)$ much below ~ 0.125. The experimental value of $\alpha_s(M_Z)$ is not a settled issue, but if the lower values (e.g., 0.110-0.115) suggested by some determinations are correct, one would have to invoke large but not unreasonable GUT or string threshold effects, NRO, or intermediate scale matter to maintain consistency.

- The MSSM couplings unify at a scale $M_X \sim 3 \times 10^{16}$ GeV. This is far enough below the Planck scale $\sim 10^{19}$ GeV that it may be consistent to consider grand unification of the strong and electroweak couplings without gravity. Nevertheless, it is tempting to bring gravity into the game. For example, one expects that in superstring compactifications the couplings will unify around the string scale $M_{\rm string} \sim g \times 5 \times 10^{17}$ GeV, which is one order of magnitude above M_X. It is possible that the string compactification first produces a grand unified theory in four dimensions, which then breaks at the lower scale M_X. However, it is difficult to find models in which this occurs and for which the necessary Higgs multiplets to break the GUT symmetry are present. Alternatively, the string compactification may lead directly to the standard model group, in which case one must invoke string threshold effects, intermediate scale matter, or higher Kač-Moody levels to explain the discrepancy of scales.

[7]Non-universal gaugino masses can lead to larger effects [28], but these would explicity break the grand unification gauge symmetry.

- Much attention has been focussed on the deviation of M_X from $M_{\rm string}$ and on the predicted $\alpha_s(M_Z)$. However, the actual unification predictions are for $\ln(M_X/M_Z)$ and $1/\alpha_s(M_Z)$. The former is consistent with the string scale to within 10% and the latter is accurate to within 15%as well. Given the enormous number of perturbations on the predictions that can occur in string and GUT models one should view the predictions as a major success for the general idea of GUT or string unification.

- Most types of new physics at the TeV scale would have very large (order 1) effects on the gauge unification prediction. Unless the success is just an accident, and barring cancellations between large effects, this severely restricts the possibilities for new physics beyond the MSSM at the TeV scale. Essentially the only possibilities are extended gauge groups which commute with the standard model group, such as additional U_1 factors associated with heavy Z' bosons, complete ordinary or mirror additional families, new exotic families which correspond to complete GUT multiplets, and standard model singlets.

3.3 Extended Technicolor/Compositeness

In contrast, the other major class of extensions, which includes compositeness and dynamical symmetry breaking, leads to many implications at low energies. The most important are large flavor changing neutral currents (FCNC). Even if these are somehow evaded one generally expects anomalous contributions to the $Z \to b\bar{b}$ vertex, typically $\Gamma(b\bar{b}) < \Gamma^{SM}(b\bar{b})$ in the simplest extended technicolor (ETC) models [29]. Similarly, one expects $\rho_0 \neq 1$, and $S \neq 0, T \neq 0$, where ρ_0, S, and T parameterize certain types of new physics, as will be described below. Finally, in theories with composite fermions one generally expects new 4-fermi operators generated by constituent interchange, leading to effective interactions of the form

$$L = \pm\frac{4\pi}{\Lambda^2}\bar{f}_1\Gamma f_2\bar{f}_3\hat{\Gamma}f_4. \tag{9}$$

Generally, the Z-pole observables are not sensitive to such operators, since they only measure the properties of the Z and its couplings[8]. However, low energy experiments are sensitive. In particular, FCNC constraints typically set limits of order $\Lambda \geq O(100 \text{ TeV})$ on the scale of the operators unless the flavor-changing effects are fine-tuned away. Even then there are significant limits from other flavor conserving observables. For example, atomic parity violation [30] is sensitive to operators such as [31]

$$L = \pm\frac{4\pi}{\Lambda^2}\bar{e}_L\gamma_\mu e_L\bar{q}_L\gamma^\mu q_L. \tag{10}$$

The existing data already sets limits $\Lambda > O(10 \text{ TeV})$. Future experiments should be sensitive to ~ 40 TeV.

3.4 The $Zb\bar{b}$ Vertex

The $Zb\bar{b}$ vertex is especially interesting, both in the standard model and in the presence of new physics. In the standard model there are special vertex contributions which depend quadratically on the top quark mass. $\Gamma(b\bar{b})$ actually decreases with m_t [32, 33], as opposed to other widths which all increase. The m_t and M_H dependences in the radiative corrections are strongly

[8]At the Z-pole the effects of new operators are out of phase with the Z amplitude and do not interfere. Interference effects can survive away from the pole, but there the Z amplitude is smaller.

correlated, but the special vertex corrections to $\Gamma(b\bar{b})$ are independent of M_H, allowing a separation of m_t and M_H effects.

The vertex is also sensitive to a number of types of new physics. One can parameterize such effects by [34]

$$\Gamma(b\bar{b}) \to \Gamma^{SM}(b\bar{b})\,(1+\delta_{bb}^{\rm new})\,. \tag{11}$$

If the new physics gives similar contributions to vector and axial vector vertices then the effects on $A_{\rm FB}^b$ are small. In supersymmetry one can have both positive and negative contributions [35]. In particular, light $\tilde{t}-\chi^{\pm}$ can give $\delta_{bb}^{\rm SUSY}>0$, as is suggested by the data, while light charged Higgs particles can yield $\delta_{bb}^{\rm Higgs}<0$. In practice, both effects are too small to be important in most allowed regions of parameter space. In extended technicolor (ETC) models there are typically new vertex contributions generated by the same ETC interactions which are needed to generate the large top quark mass. It has been argued that these are typically large and negative [29],

$$\delta_{bb}^{\rm ETC} \sim -0.056\xi^2\left(\frac{m_t}{150{\rm GeV}}\right), \tag{12}$$

where ξ is a model dependent parameter of order unity. They may be smaller in models with walking technicolor, but nevertheless are expected to be negative and significant [36]. This is in contrast to the data, which suggests a positive contribution if any, implying a serious problem for many ETC models. Possible ways out are models in which the ETC and electroweak groups do not commute, for which either sign is possible [37], models in which diagonal interactions related to extended technicolor dominate [38], and topcolor or topcolor assisted technicolor models, for which the ETC contribution to m_t is small [39].

Another possibility is mixing between the b and exotic heavy fermions with non-canonical weak interaction quantum numbers. Many extensions of the standard model predict, for example, the existence of a heavy D_L, D_R, which are both SU_2 singlet quarks with charge $-1/3$. These can mix with the d, s, or b quarks, but one typically expects such mixing to be largest for the third generation. However, this mechanism gives a negative contribution

$$\delta_{bb}^{D_L} \sim -2.3 s_L^2 \tag{13}$$

to $\delta_{bb}^{\rm new}$, where s_L is the sine of the $b_l - D_L$ mixing angle.

One can extract $\delta_{bb}^{\rm new}$ from the data, in a global fit to the standard model parameters as well as $\delta_{bb}^{\rm new}$. This yields

$$\delta_{bb}^{\rm new} = 0.032 \pm 0.010, \tag{14}$$

which is $\sim 3.2\sigma$ above zero. This value is hardly changed when one allows additional new physics, such as described by the S, T, and U parameters. $\delta_{bb}^{\rm new}$ is correlated with $\alpha_s(M_Z)$: one obtains $\alpha_s(M_Z) = 0.101 \pm 0.008$, considerably smaller than the standard model value 0.123(4)(2). Allowing $\delta_{bb}^{\rm new} \neq 0$ has negligible effect on $\hat{s}_Z^2$ or m_t.

In a more detailed analysis [3] one can allow separate corrections in the left and right-handed b couplings,

$$g_{Lb} = \frac{1}{2}(g_{Vb}+g_{Ab}) \to -\frac{1}{2}+\frac{1}{3}\sin^2\theta_W + \delta_L^b, \tag{15}$$

and

$$g_{Rb} = \frac{1}{2}(g_{Vb}-g_{Ab}) \to \frac{1}{3}\sin^2\theta_W + \delta_R^b. \tag{16}$$

Then R_b, A_{FB}^{0b} and the other observables can be used to simultaneously constrain δ_L^b, δ_R^b, and the other parameters. From the global fit

$$\delta_L^b = -0.0033 \pm 0.0035 \qquad \delta_R^b = 0.018 \pm 0.013, \tag{17}$$

Figure 4: Allowed regions in δ_L^b vs δ_R^b for $M_H = 300$ GeV.

with a correlation of 0.80. These should be compared with the unperturbed standard model values $g_{Lb} = -0.421$ and $g_{Rb} = 0.077$, respectively. One also obtains the low value $\alpha_s(M_Z) = 0.101 \pm 0.008$, just as in the single parameter case. At their central values δ_L^b and δ_R^b contribute about equally to R_b, while their effects partially cancel in A_{FB}^{0b}, which is consistent with the standard model. The allowed region in $\delta_L^b - \delta_R^b$ is shown in Figure 4. One sees that there is a tendency from the anomaly to be in δ_R^b, but it cannot be excluded that the effect is in δ_L^b or a mixture.

3.5 ρ_0: Nonstandard Higgs or Non-degenerate Heavy Multiplets

One parameterization of certain new types of physics is the parameter ρ_0, which is introduced to describe new sources of SU_2 breaking other than the ordinary Higgs doublets or the top/bottom splitting. One defines $\rho_0 \equiv M_W^2/(M_Z^2 \hat{c}_Z^2 \hat{\rho})$, where $\hat{c}_Z^2 \equiv 1 - \hat{s}_Z^2$; $\hat{\rho} \sim 1 + 3G_F m_t^2/8\sqrt{2}\pi^2$ absorbs the relevant standard model radiative corrections so that $\rho_0 \equiv 1$ in the standard model. New physics can affect ρ_0 at either the tree or loop-level

$$\rho_0 = \rho_0^{\text{tree}} + \rho_0^{\text{loop}}. \tag{18}$$

The tree-level contribution is given by Higgs representations larger than doublets, namely,

$$\rho_0^{\text{tree}} = \frac{\sum_i \left(t_i^2 - t_{3i}^2 + t_i\right) |\langle\phi_i\rangle|^2}{\sum_i 2t_{3i}^2 |\langle\phi_i\rangle|^2}, \tag{19}$$

where t_i (t_{3i}) is the weak isospin (third component) of the neutral Higgs field ϕ_i. For Higgs singlets and doublets ($t_i = 0, \frac{1}{2}$) only, $\rho_0^{\text{tree}} = 1$. However, in the presence of larger representations with non-zero vacuum expectation values

$$\rho_0^{\text{tree}} \simeq 1 + 2\sum_i \left(t_i^2 - 3t_{3i}^2 + t_i\right) \frac{|\langle\phi_i\rangle|^2}{|\langle\phi_{\frac{1}{2}}\rangle|^2}. \tag{20}$$

One can also have loop-induced contributions similar to that of the top/bottom, due to non-degenerate multiplets of fermions or bosons. For new doublets

$$\rho_0^{\text{loop}} = \frac{3G_f}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3} F(m_{1i}, m_{2i}), \tag{21}$$

where $C_i = 3(1)$ for color triplets (singlets) and

$$\begin{aligned} F(m_1, m_2) &= m_1^2 + m_2^2 - \frac{4m_1^2\, m_2^2}{m_1^2 - m_2^2} \ln \frac{m_2}{m_2} \\ &\geq (m_1 - m_2)^2. \end{aligned} \tag{22}$$

Figure 5: Allowed regions in ρ_0 vs $\hat{s}^2_Z$ for $M_H = 60$, 300, and 1000 GeV.

Loop contributions to ρ_0 are generally positive,[9] and if present would lead to lower values for the predicted m_t. $\rho_0^{\rm tree} - 1$ can be either positive or negative depending on the quantum numbers of the Higgs field. The ρ_0 parameter is extremely important because one expects $\rho_0 \sim 1$ in most superstring theories, which generally do not have higher-dimensional Higgs representations, while typically $\rho_0 \neq 1$ from many sources in models involving compositeness.

In the presence of ρ_0 the standard model formulas for the observables are modified. One has

$$M_Z \to \frac{1}{\sqrt{\rho_0}} M_Z^{SM}, \quad \Gamma_Z \to \rho_0 \Gamma_Z^{SM}, \quad \mathcal{L}_{NC} \to \rho_0 \mathcal{L}_{NC}^{SM}. \tag{23}$$

It has long been known that ρ_0 is close to 1. However, until recently it has been difficult to separate ρ_0 from m_t, because in most observables one has only the combination $\rho_0 \hat{\rho}$. The one exception has been the $Z \to b\bar{b}$ vertex. However, the direct observation of the t by CDF and D0, with their average $m_t = 180 \pm 12$ GeV, allows one to calculate $\hat{\rho}$ and therefore separate ρ_0. In practice one fits to m_t, ρ_0 and the other parameters, using the CDF/D0 value of m_t as an additional constraint. One can determine $\hat{s}^2_Z$, ρ_0, m_t, and α_s simultaneously, yielding

$$\begin{aligned} \rho_0 &= 1.0012 \pm 0.0013 \pm 0.0018 \\ \hat{s}^2_Z &= 0.2314(2)(2) \\ \alpha_s &= 0.121(4)(1) \\ m_t &= 171 \pm 12 \text{ GeV}, \end{aligned} \tag{24}$$

where the second uncertanty is from M_H. Even in the presence of the classes of new physics parameterized by ρ_0 one still has robust predictions for the weak angle and a good determination of α_s. Most remarkably, given the CDF/D0 constraint, ρ_0 is constrained to be very close to unity, causing serious problems for compositeness models. The allowed region in ρ_0 vs $\hat{s}^2_Z$ are shown in Figure 5. This places limits $|\langle\phi_i\rangle|/|\langle\phi_{1/2}\rangle| <$ few% on non-doublet vacuum expectation values, and places constraints $\frac{C}{3} F(m_1, m_2) \leq (100 \text{ GeV})^2$ on the splittings of additional fermion or boson multiplets.

3.6 Heavy Physics by Gauge Self Energies

A larger class of extensions of the standard model can be parameterized by the S, T and U parameters [42], which describe that subset of new physics which affect only the gauge boson

[9]One can have $\rho^{\rm loop} < 0$ for Majorana fermions [40] or boson multiplets with vacuum expectation values [41].

self-energies but do not directly affect new vertices, etc. One introduces three parameters[10]

$$\begin{aligned} S &= S_{\text{new}} + S_{m_t} + S_{M_H} \\ T &= T_{\text{new}} + T_{m_t} + T_{M_H} \\ U &= U_{\text{new}} + U_{m_t}. \end{aligned} \tag{25}$$

S describes the breaking of the SU_{2A} axial generators and is generated, for example, by degenerate heavy chiral families of fermions. T and U describe the breaking of SU_{2V} vector generators: T is equivalent to the ρ_0 parameter and is induced by mass splitting in multiplets of fermions or bosons. U is zero in most extensions of the standard model. S, T and U were introduced to describe the contributions of new physics. However, they can also parametrize the effects of very heavy m_t and M_H (compared to M_Z). Until recently it was difficult to separate the m_t and new physics contributions. Now, however, with the CDF/D0 measurement of m_t it is possible to directly extract the new physics contributions. In the following, I will use S, T, and U to represent the effects of new physics only, with the m_t and M_H effects on observables included separately.

A new multiplet of degenerate chiral fermions will contribute to S by

$$S|_{\text{degenerate}} = C_i |t_{3L}(i) - t_{3R}(i)|^2 / 3\pi \geq 0, \tag{26}$$

where C_i is the number of colors and t_{3LR} are the t_3 quantum numbers. A fourth family of degenerate fermions would yield $\frac{2}{3\pi} \sim 0.21$, while QCD-like technicolor models, which typically have many particles, can give larger contributions. For example, $S \sim 0.45$ from an isodoublet of fermions with four technicolors, and an entire technigeneration would yield 1.62 [44]. Non-QCD-like theories such as those involving walking could yield smaller or even negative contributions [45]. Loops involving scalars, nondegenerate fermions, or Majorana particles can contribute to S with either sign [46]. (Note that S, T, and U are induced by loop corrections and have a factor of α extracted, so they are expected to be $O(1)$ if there is new physics.)

The T parameter is analogous to ρ_0^{loop}. For a non-degenerate family

$$T \sim \frac{\rho_0^{\text{loop}}}{\alpha} \sim 0.42 \frac{\Delta m^2}{(100\ GeV)^2}, \tag{27}$$

where

$$\Delta m^2 = \sum_i \frac{C_i}{3} F\left(m_{1i}, m_{2i}\right). \tag{28}$$

Usually $T > 0$, although there may be exceptions for theories with Majorana fermions or additional Higgs doublets. In practice, higher-dimensional Higgs multiplets could mimic T with either sign (see equation (19)), and cannot be separated from loop effects unless they are seen directly or have other effects. I will therefore deviate slightly from the historical definition and redefine T to include the tree level effects of such multiplets, so that

$$\rho_0 = \frac{1}{1 - \alpha T} \simeq 1 + \alpha T. \tag{29}$$

Usually U is small.

There is enough data to simultaneously determine the new physics contributions to S, T, and U, the standard model parameters, and also $\delta_{bb}^{\text{new}} = \frac{\Gamma(b\bar{b})}{\Gamma^{\text{SM}}(b\bar{b})} - 1$. For example, S, T, U, δ_{bb}^{new},

[10] Three additional parameters are needed if the new physics scale is comparable to M_Z [43].

$\hat{s}_Z^2$, $\alpha_s(M_Z)$ and m_t are constrained by M_Z, Γ, M_W, R_b, asymmetries, R, and m_t (CDF/D0), respectively. One obtains

$$\begin{aligned}
S &= -0.28 \pm 0.19^{-0.08}_{+0.17} \\
T &= -0.20 \pm 0.26^{+0.17}_{-0.12} \\
U &= -0.31 \pm 0.54 \\
\delta_{bb}^{\rm new} &= 0.032 \pm 0.010 \\
\hat{s}_Z^2 &= 0.2311(3) \\
\alpha_s(M_Z) &= 0.103(8) \\
m_t &= 181 \pm 12 \text{ GeV},
\end{aligned} \tag{30}$$

where the second error is from M_H. The T value corresponds to $\rho_0 = 0.9985 \pm 0.0019^{+0.0012}_{-0.0009}$, which differs from the value in (24) because of the presence of S, U, and $\delta_{bb}^{\rm new}$. The data is consistent with the standard model: S and T are consistent with the standard model expectation of 0 at or near the 1σ level, although there is a small tendency for negative values. The constraints on S are a problem for those classes of new physics such as QCD-like technicolor which tend to give S large and positive, and S allows, at most, one additional family of ordinary or mirror fermions at 95% CL. (Of course the invisible Z width precludes any new families unless the additional neutrinos are heavier than $M_Z/2$.) The allowed regions in S vs T are shown in Figure 6. The seven parameter fit still favors a non-zero $Z \to b\bar{b}$ vertex correction $\delta_{bb}^{\rm new}$. As in the model with $S = T = U = 0$, the extracted $\alpha_s(M_Z)$ is strongly correlated with $\delta_{bb}^{\rm new}$. For $\delta_{bb}^{\rm new} = 0$ one would obtain $\alpha_s(M_Z) = 0.122(5)$.

Figure 6: Constraints on S and T from various observables and from the global fit to all data. S and T represent the effects of new physics only; uncertainties from m_t are included in the errors.

4 Conclusions

- The precision data have confirmed the standard electroweak model. However, there are possible hints of discrepancies at the $2-3\ \sigma$ level in $\Gamma(b\bar{b})/\Gamma(\text{had})$ and A^0_{LR}.

- The data not only probes the tree-level structure, but the electroweak loops have been observed at the 2σ level. These consist of much larger fermionic pieces involving the top quark and QED, which only partially cancel the bosonic loops. The bosonic loops, which probe non-abelian vertices and gauge-Higgs vertices, are definitely needed to describe the data.

- The global fit to the data (including the constraint $m_t = 180 \pm 12$ GeV from CDF and D0) within the standard model yields

$$\begin{aligned} \overline{MS} : \hat{s}_Z^2 &= 0.2315(2)(3) \\ \text{on} - \text{shell} : s_W^2 &\equiv 1 - \frac{M_W^2}{M_Z^2} = 0.2236(8) \\ m_t &= 180 \pm 7\,^{+12}_{-13} \\ \alpha_s(M_Z) &= 0.123(4)(2), \end{aligned} \tag{31}$$

  where the second uncertainty is from M_H. A fit to the indirect data only yields the prediction $m_t = 179 \pm 8\,^{+17}_{-20}$ GeV, in remarkable agreement with the direct CDF/D0 value. The data also allow a clean and precise extraction of α_s from the lineshape. This is in excellent agreement with the value $\alpha_s(M_Z) = 0.123 \pm 0.006$ from event shapes. Both are larger than many of the low energy determinations when extrapolated to the Z-pole. The lineshape determination, however, is sensitive to the presence of certain types of new physics.

- The agreement between the indirect prediction for m_t with the direct CDF/D0 observation, and of α_s with the various other determinations is an impressive success for the entire program of precision observables.

- Combining the direct CDF/D0 value of m_t with the indirect constraints does not make a large difference within the context of the standard model. However, when one goes beyond the standard model, the direct m_t allows a clean extraction of the new physics contributions to ρ_0, which is now shown to be very close to unity, $\rho_0 = 1.0012(13)(18)$. This strongly limits Higgs triplet vacuum expectation values and non-degenerate heavy multiplets. Similarly, it allows an extraction of the new physics contributions to S, T, U, which are consistent with zero. Finally, one can determine the new physics contributions to the $b\bar{b}$ vertex: δ_{bb}^{new} is approximately 3.2σ away from zero, reflecting the large value of the $b\bar{b}$ width.

- The data exhibit a preference for a light Higgs. One finds $M_H \leq 320(420)$ GeV at 90(95%) CL. However, the preference depends crucially on the observed values of R_b and A_{LR}^0, both of which differ significantly from the standard model expectations. If these are due to new physics, the M_H constraint is relaxed or disappears.

- The major prediction of supersymmetry is that one does not expect large deviations in the precision observables. The new particles tend to be heavy and decouple. One implication that is relevant, however, is that supersymmetric theories have a light standard model-like Higgs. They therefore favor the lighter Higgs mass and the lower end of the predicted m_t range.

- The observed gauge couplings are consistent within 15% with the coupling constant unification expected in supersymmetric grand unification, but not with the simplest version of non-supersymmetric unification. The logarithm of the unification scale is also consistent within 10% with the expectations of superstring compactifications which break directly to the standard model group. Perhaps we should take this as a hint that the grand desert hypothesis is correct, and focus on GUTs and string compactifications for which threshold and new particle effects are small (of order 10%).

- In compositeness and dynamical symmetry breaking theories one typically expects not only large flavor changing neutral currents but significant deviations of ρ_0 from unity and of S and T from zero. One further expects that $\delta_{bb}^{\rm new} < 0$, at least in the simplest models. Therefore, the precision experiments are a major difficulty for this class of models.

Acknowledgement

It is a pleasure to thank Jens Erler for collaboration on these analyses. I would also like to thank the conference organizers for travel support. This work was supported by U.S. Department of Energy Grant No. DOE-EY-76-02-3071 and the National Science Foundation Grant No. PHY94-07194.

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